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VTOL HEIGHT-CONTROL REQUIREMENTS IN HOVERING AS DETERMINED FROM MOTION SIMULATOR STUDY

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SUMMARY

Flight experience with recent VTOL aircraft and a consideration of future VTOL configurations indicate several possible sources for unsatisfactory height-control characteristics. These unsatisfactory characteristics, which are essentially foreign to the helicopter, include low maximum thrust-weight ratio for even short time intervals (applies to aircraft having low usable lifting system inertia which does not provide stored energy for momentary additional thrust), near zero vertical-velocity damping force, a time delay in acceleration response to control inputs, and zero or unstable ground effect.

In an effort to determine the extent to which these potential problem areas influence height control, an investigation was conducted by using an available single-degree-of-freedom simulator. During the testing the pilot executed rapid altitude changes with a minimum of overshoot. The results of these tests suggest that satisfactory control for a well-damped aircraft (damping-mass ratio of 0.7 to 1.0 per second) can be obtained by a minimum thrust-weight ratio of 1.08. A damping-mass ratio of 0.2 per second was found to be a minimum to obtain satisfactory control. Introduction of a control-system time delay resulted in a rapid deterioration in hovering controllability which, however, was substantially offset by increased vertical-velocity damping. The addition of stable ground effect to the simulation improved controllability for all the conditions of damping tested. For the range of unstable ground effect investigated, only a slight loss in control precision was noted.

INTRODUCTION

Flight experience with recent VTOL aircraft, as well as a consideration of future VTOL design configurations, has indicated several possible sources for unsatisfactory height-control characteristics. Unsatisfactory height-control characteristics (which, if encountered at all in the helicopter, occur to a much lesser degree) have been attributed generally to one or more of the following conditions: (1) low maximum thrust-weight ratio for even short time intervals (applies to aircraft having low usable lifting system inertia which, therefore, does not provide stored energy for additional thrust on a temporary basis), (2) lack of inherent vertical-velocity damping force, (3) appreciable engine response time resulting in a lag in the acceleration response to control inputs; this condition is especially troublesome in configurations in which thrust is solely dependent on engine speed or when little stored energy is available, and (4) negative ground effect which produces a loss in lift when operating near the ground.

A previous investigation (ref. 1) was conducted with a fixed-base simulator for the purpose of obtaining preliminary information with respect to the effects of these problems on height-control characteristics. Previous studies have shown that results obtained from a fixed-base simulator are apt to be unduly conservative, particularly if the pilot must rely entirely on instrumentation to provide motion cues. On the other hand, the inclusion of actual motion into the simulation enables the pilot to cope with some characteristics considered uncontrollable otherwise.

In an effort to obtain further information relative to VTOL height-control requirements by the addition of motion to the simulation, the present investigation was conducted by using an available single-degree-of-freedom motion simulator. Initial tests were performed to establish an optimum control sensitivity (vertical acceleration per unit control travel) for use throughout the remainder of the test. Next, various combinations of maximum thrust-weight ratio and vertical-velocity damping were simulated and pilot-opinion boundaries were obtained. Finally, the effects of control-system time delay and ground effect were investigated.

SYMBOLS

D damping, lb/ft/sec

g acceleration due to gravity, 32.2 ft/sec^2

k ground effect parameter, ft/sec^2/ft

m mass, slugs

T thrust, lb

W weight, lb

DESCRIPTION OF TEST EQUIPMENT AND TESTS

Test Equipment

The single-degree-of-freedom motion simulator used in the investigation consisted essentially of a hydraulically powered cockpit which was coupled to an analog computer. The cockpit, which is shown schematically in figure 1, was constrained to move along the vertical axis and responded to pilot-control inputs in accordance with the equations of motion programed in the analog computer. A detailed description of the motion simulator is given in reference 2. The function of the analog computer in the simulation is represented by the block diagram in figure 2.

Comparison of the cockpit's actual motion with its theoretical response to a step input indicated an effective time delay (pure transport-type delay plus time-constant-type lag) of 0.19 ± 0.02 second. This apparent lag in the simulator's response was considered acceptable for the completion of the test program. The useful vertical linear travel of the cockpit was limited to 8 feet. A helicopter-type collective stick, with adjustable friction, was located on the left side of the cockpit. It should be noted that the study reported in reference 3 found no significant difference in the results obtained by using a collective stick as opposed to a quadrant control.

Tests

The primary task used during the test program consisted of executing altitude changes and stabilizing at the new altitude as rapidly as possible and with a minimum of overshoot in the absence of simulated gust inputs. An indication of aircraft altitude was provided by projecting a light beam from the cockpit onto a marked screen located several feet in front of the cockpit. The pilots were instructed to judge the height-control characteristics of each simulated configuration while using the arm-shoulder control technique. The arm-shoulder technique, as the name implies, involves motion of the arm and shoulder while controlling as opposed to the finger-type control technique with the arm and shoulder stationary. The Cooper pilot opinion rating system, described in reference 4 and used in the evaluation, is presented in table I. Two NASA research pilots evaluated identical test conditions and their ratings were averaged for purposes of presenting the results. It was noted during the testing that the pilots tended to subdivide the pilot opinion rating system as finely as quarter units in order to indicate small but perceptible changes in controllability. Although this fine splitting of the rating system is of no significance in comparing one group of data with another, it is beneficial for establishing threshold values for changes in a test condition within the framework of a given study.

RESULTS AND DISCUSSION

Control Sensitivity

To establish an optimum level for control sensitivity, that is, vertical acceleration per unit control travel, various combinations of sensitivity and vertical-velocity damping were simulated. The values of these parameters included a sensitivity range of 0.15g per inch to 0.62g per inch and a damping-mass ratio range of -0.4 per second to 2 per second. For stable damping the reciprocal of the damping-mass ratio represents the time for the vehicle to reach 63 percent of its steady-state velocity following a control input and is denoted herein by a positive sign. Throughout the simulations of control sensitivity, the maximum available thrust-weight ratio was kept sufficiently high (greater than 1.4) so as not to influence the selection of optimum sensitivities.

The results of these tests are mapped on a damping-mass—sensitivity plane in figure 3. The curve labeled "$3\frac{1}{2}$ boundary" represents a boundary between satisfactory and unsatisfactory. The range of parameters tested did not warrant ratings which would permit the mapping of the usual "$6\frac{1}{2}$ boundary" (boundary between unsatisfactory and unacceptable); therefore, a "$5\frac{1}{2}$ boundary" was mapped for an indication of gradient only. The "optimum ratio line" indicates the best control sensitivity for a given amount of vertical-velocity damping. Test combinations to the left of the "optimum" ratio line yielded a sluggish response; for combinations to the right there was a tendency to overshoot and overcontrol. Thus, for an aircraft (such as the helicopter) with a damping-mass ratio equal to about 1, the desirable sensitivity appears to be about 0.25g per inch; for an aircraft with zero damping, a sensitivity of 0.15g per inch appears to be desirable.

Maximum Thrust-Weight Ratio

In figure 4 the results of the maximum thrust-weight ratio studies are mapped on the damping-mass—thrust-weight plane. These tests were performed at a sensitivity of 0.3g per inch while the thrust-weight ratio was varied from 1.05 to 1.3 and the damping-mass ratio was varied from 0 to 1 per second. In addition to a "$3\frac{1}{2}$ boundary," the averaged pilot ratings, which were obtained for each test condition, are located on the figure as an indication of gradient. The results obtained from reference 1 are designated by the dashed line curves and are presented for comparison.

Figure 4 indicates that satisfactory control can be obtained with a thrust-weight ratio as low as 1.08 if the aircraft is well damped. For an aircraft with a high thrust-weight ratio, satisfactory control can be obtained by a minimum damping-mass ratio of 0.2 per second. Comparison with the fixed-base simulator results of reference 1 (dashed line curves) suggests that the addition of motion cues, as was done in the present simulation, resulted in a marked improvement in the controllability for a given combination of thrust weight and damping. For example, with the addition of motion cues to the simulation, the minimum satisfactory thrust-weight ratio decreased from greater than 1.19 to about 1.08.

Control-System Time Delay

The effect of a control-system time delay (a delay in the vertical acceleration response to a control input) was studied by electrically modifying the control input with a network which introduced a first-order time delay. The time specified for the delay represents the number of seconds for the acceleration response to reach 63 percent of the pilot-commanded acceleration. With the effective 0.2-second time delay already present in the simulator taken into account, the delay was varied from 0.2 to 1.2 seconds for three different combinations of thrust-weight ratio T/W and damping-mass ratio D/m, and at a constant sensitivity of 0.3g per inch. The combinations of T/W and D/m used are as follows:

Combination	T/W	D/m
I	1.2	1
II	1.2	0
III	1.05	0.5

Inspection of figure 5 indicates a deterioration of rating with increased time delay for all cases tried. Upon further inspection it will be noted that an increase in time delay results in a greater rate of control deterioration for the condition of high thrust-weight ratio, either with or without damping, than for a low thrust-weight ratio. A similar trend was encountered in the fixed-base simulation studies of reference 1. This effect is clearly demonstrated by the fact that the test combination of high thrust-weight ratio and high damping represented by curve I (which normally provides good handling qualities) was rated worse than the low thrust-weight ratio and lower damping combination of curve III when the time constant was greater than 0.5 second. Pilot commentary indicated that, with an available high thrust-weight ratio, increasing the time constant above 0.3 to 0.4 second resulted in a disproportionately rapid loss in precision due to overcontrolling and pilot-induced oscillations.

The fact that there is less tendency toward overcontrolling for the case of low thrust-weight ratio stems largely from the fact that there is little control margin to permit much overcontrolling regardless of the magnitude of delay. Furthermore, with the low thrust margin, the pilot is limited to much slower maneuvering, which minimizes the tendency to overshoot and the subsequent tendency toward pilot-induced oscillations. This result should not be construed as advocating a reduction in maximum thrust weight to cure control problems resulting from a control-system time delay. Rather the pilot is limited to the use of smaller and more deliberate control motions when a great deal of precision is required. On the other hand, pilot commentary, as well as figure 5, indicates that increased damping is highly beneficial in enabling the pilot to cope with the delay.

Comparison of certain test results from figure 5 with those for identical test conditions from previous parts of the test program indicates a shift in pilot ratings in the direction showing improved handling qualities. For example, in figure 5 the test combination represented by curve I and a time delay of 0.2 second was rated 2.5; whereas the same condition in figure 4 was rated 3. No attempt has been made to correlate these apparent discrepancies which are probably caused by a slightly different pilot viewpoint and reference as well as by increased familiarity with the system and task.

Ground Effect

During operation very near the ground, VTOL aircraft may experience a change in thrust proportional to the height above the ground. This phenomenon, which is known as ground effect, is termed positive, or stable, when the thrust increases with decreased height. Thus, if the control is displaced, the aircraft will translate to and (in the presence of stable damping) remain at a new equilibrium altitude rather than assume a constant vertical velocity. Because of peculiar flow characteristics, some configurations have exhibited a loss-in-lift tendency near the ground which is termed negative, or unstable, ground effect.

Figure 6 shows the variation in maximum thrust-weight ratio with altitude as produced by the simulated ground effect. The ground effect parameter k, which was defined as the change of maximum-acceleration capability with altitude for use in the simulation equations, was varied from -0.257 ft/sec^2/ft to 0.483 ft/sec^2/ft.

Because of the simulator's limited range of travel, it was not considered feasible to make a study of ground effect from the standpoint of arresting rates of descent. However, its effect on the precision of executing altitude changes was studied with the thrust-weight ratio of 1.2 established at zero altitude. Typical heights used ranged from 2 to 7 feet. It may be seen from figure 7 that positive ground effect resulted in an improvement in controllability for all values of damping simulated. On the other hand, for the range of negative ground effect investigated, there was only a very slight deterioration in hovering controllability. In contrast with the studies of reference 1, the pilots noted no objectionable tendencies toward oscillations at the higher positive ground effect even with zero damping.

CONCLUSIONS

A motion-simulator study of VTOL height-control requirements, has been conducted during which the pilot executed small altitude changes as rapidly as possible and with a minimum of overshoot in the absence of simulated gust inputs. From this study the following conclusions are drawn:

1. Desirable controller sensitivity is a function of vertical-velocity damping and varies from a value of approximately 0.25g per inch for damping-mass ratio of 1 per second to a value of 0.15g per inch for zero damping.

2. Satisfactory control for a well-damped aircraft can be obtained by a thrust-weight ratio as low as 1.08 without benefit of stored energy. For an aircraft with a high thrust-weight ratio, satisfactory control can be obtained by a minimum damping mass of about 0.2 per second.

3. Increasing control-system time delay results in a deterioration of controllability. Although increased damping is beneficial in enabling the pilot to cope with the delay, none of the combinations tested gave satisfactory control with time delays greater than about 0.4 second.

4. There is a slight tendency toward more precise height controllability as ground effect is varied from unstable to stable values.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 17, 1962.

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3. A'Harrah, R. C., and Kwiatkowski, S. F.: A New Look at V/STOL Flying Qualities. Paper No. 61-62, Inst. Aerospace Sci., Jan. 1961.

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TABLE I.- COOPER PILOT-OPINION RATING SYSTEM

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter.

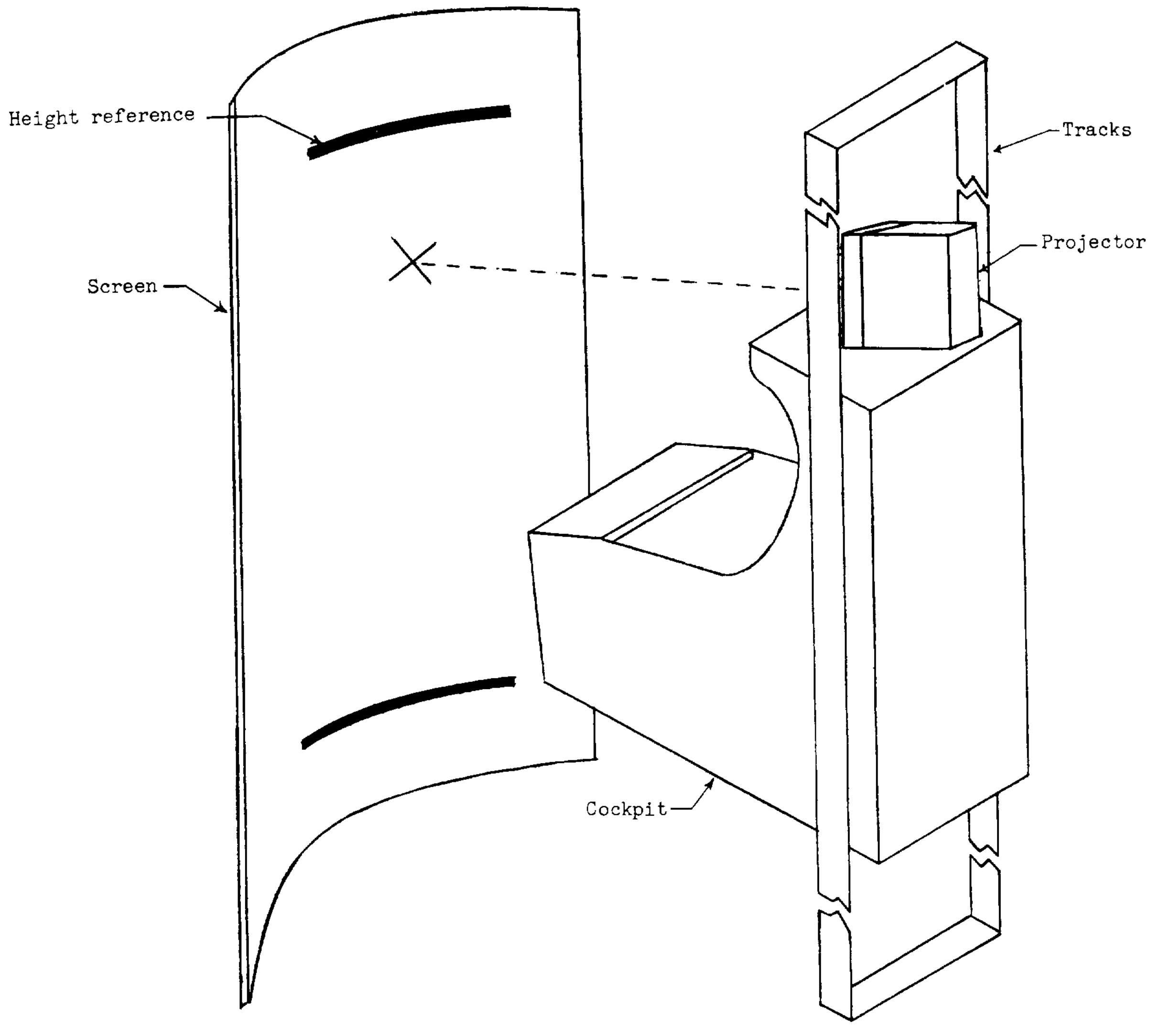

Figure 1.- Schematic of vertical motion simulator.

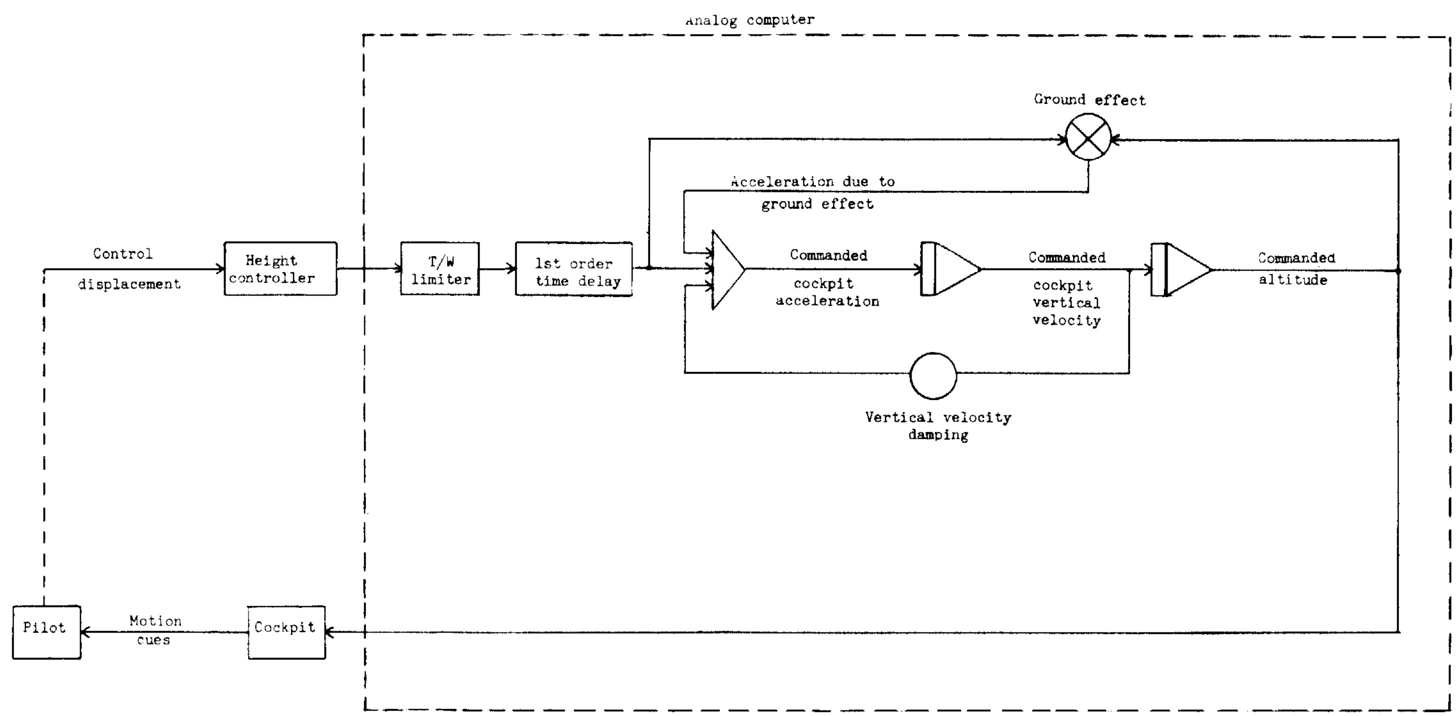

Figure 2.- Block diagram of simulator.

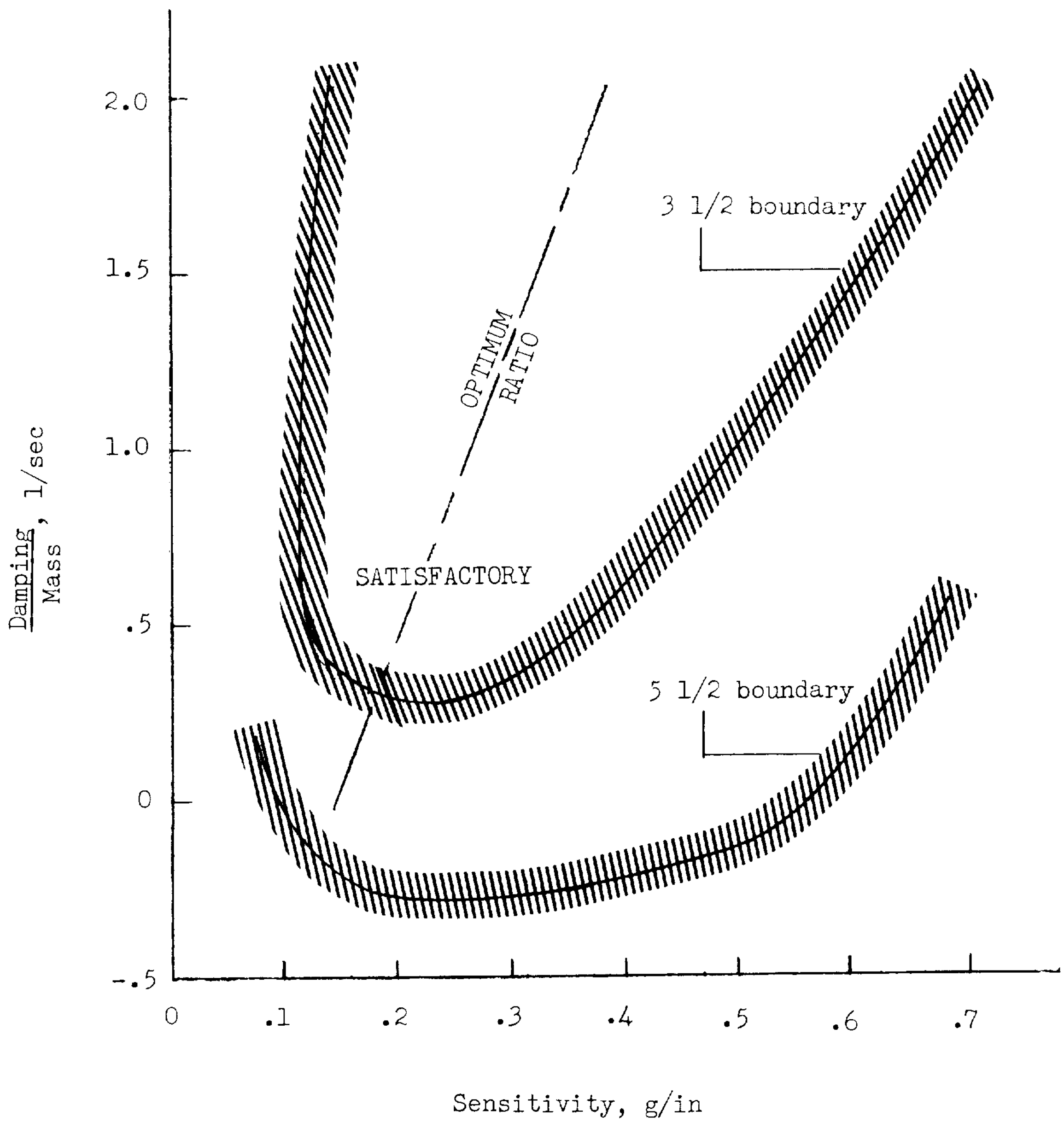

Figure 3.- Control sensitivity boundaries with zero ground effect and effective 0.2-second control-system time delay.

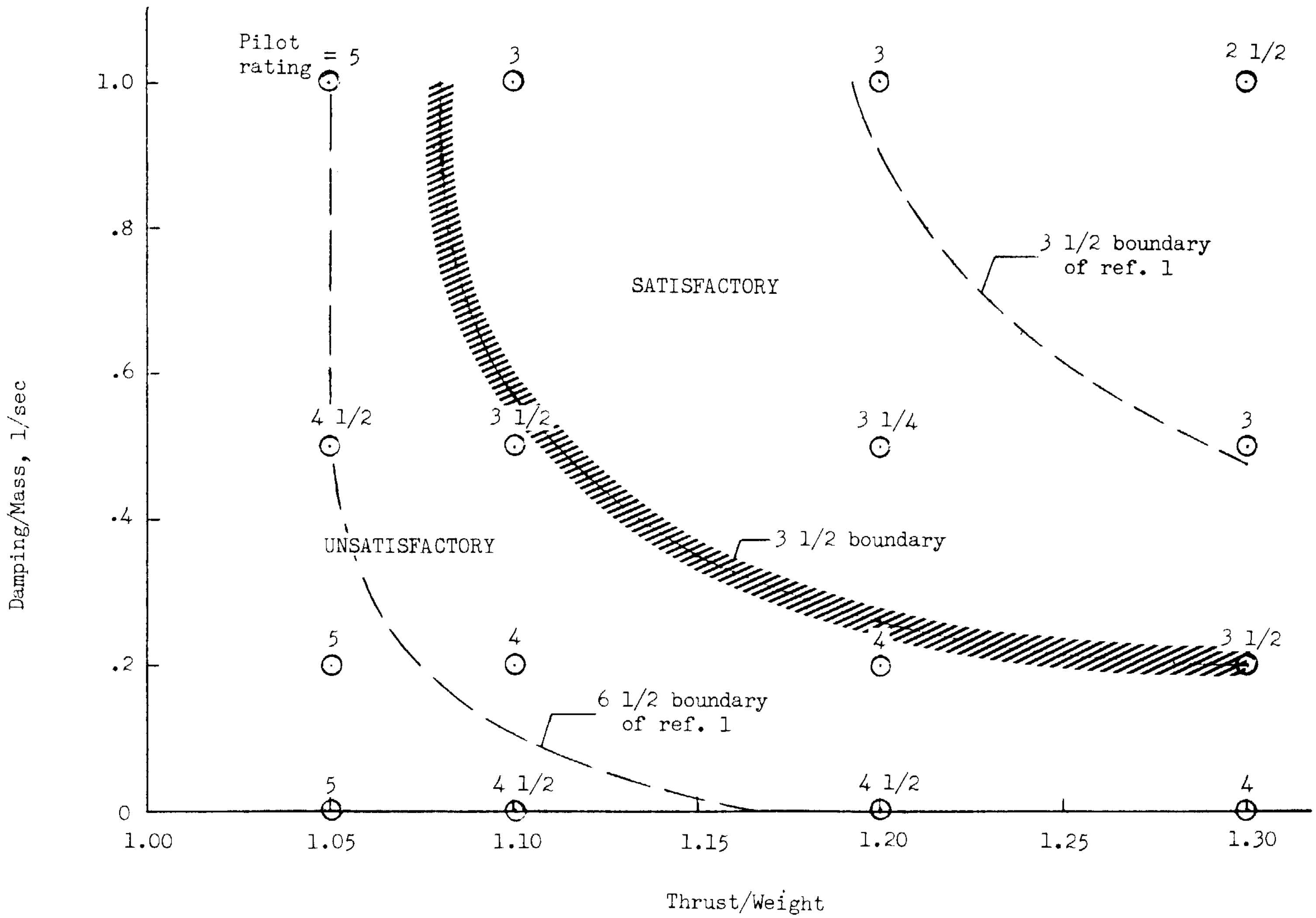

Figure 4.- Maximum thrust-weight boundaries with zero ground effect and effective 0.2 second control-system time delay.

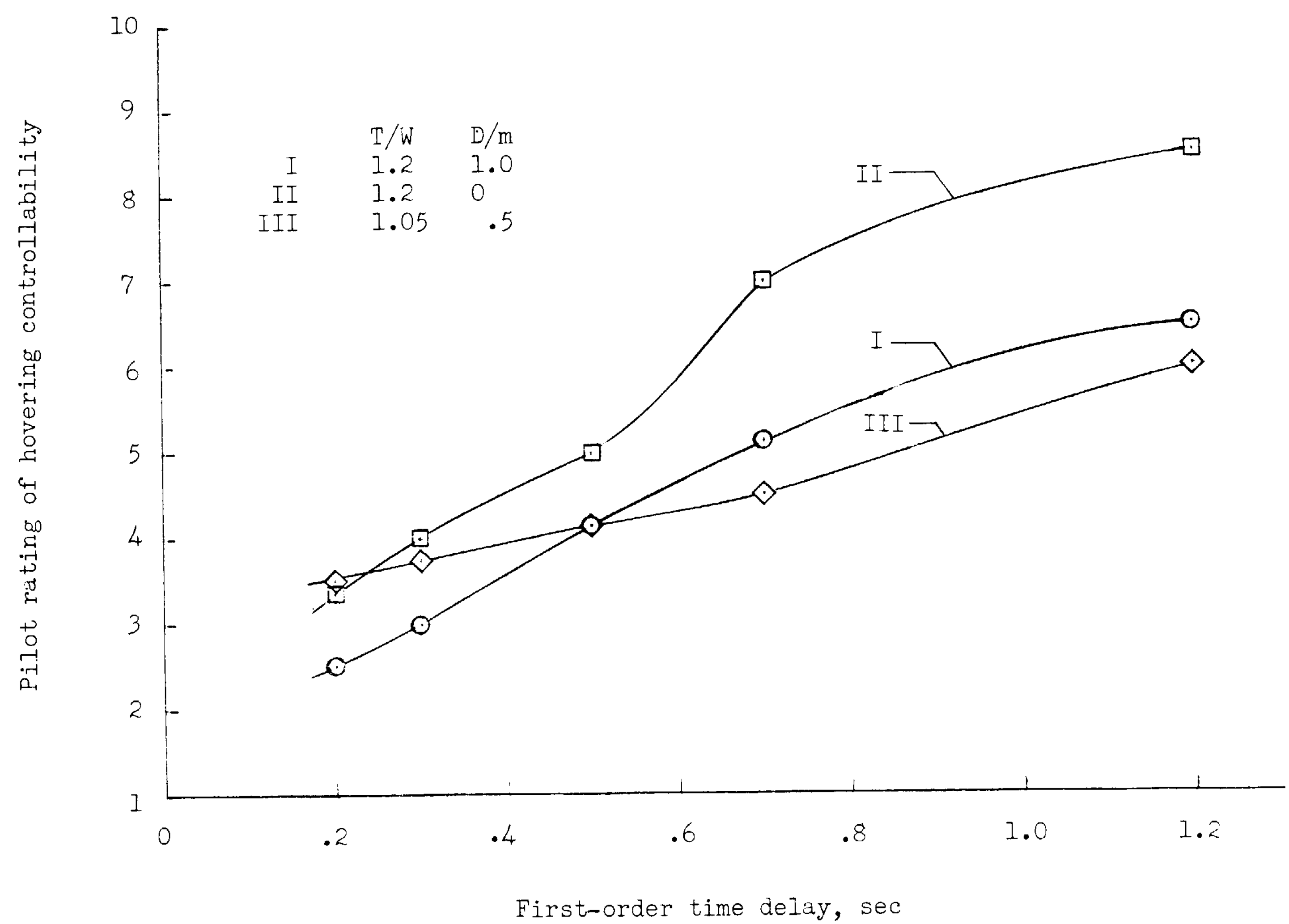

Figure 5.- Variation in pilot rating of overall controllability due to control-system time delay out of ground effect.

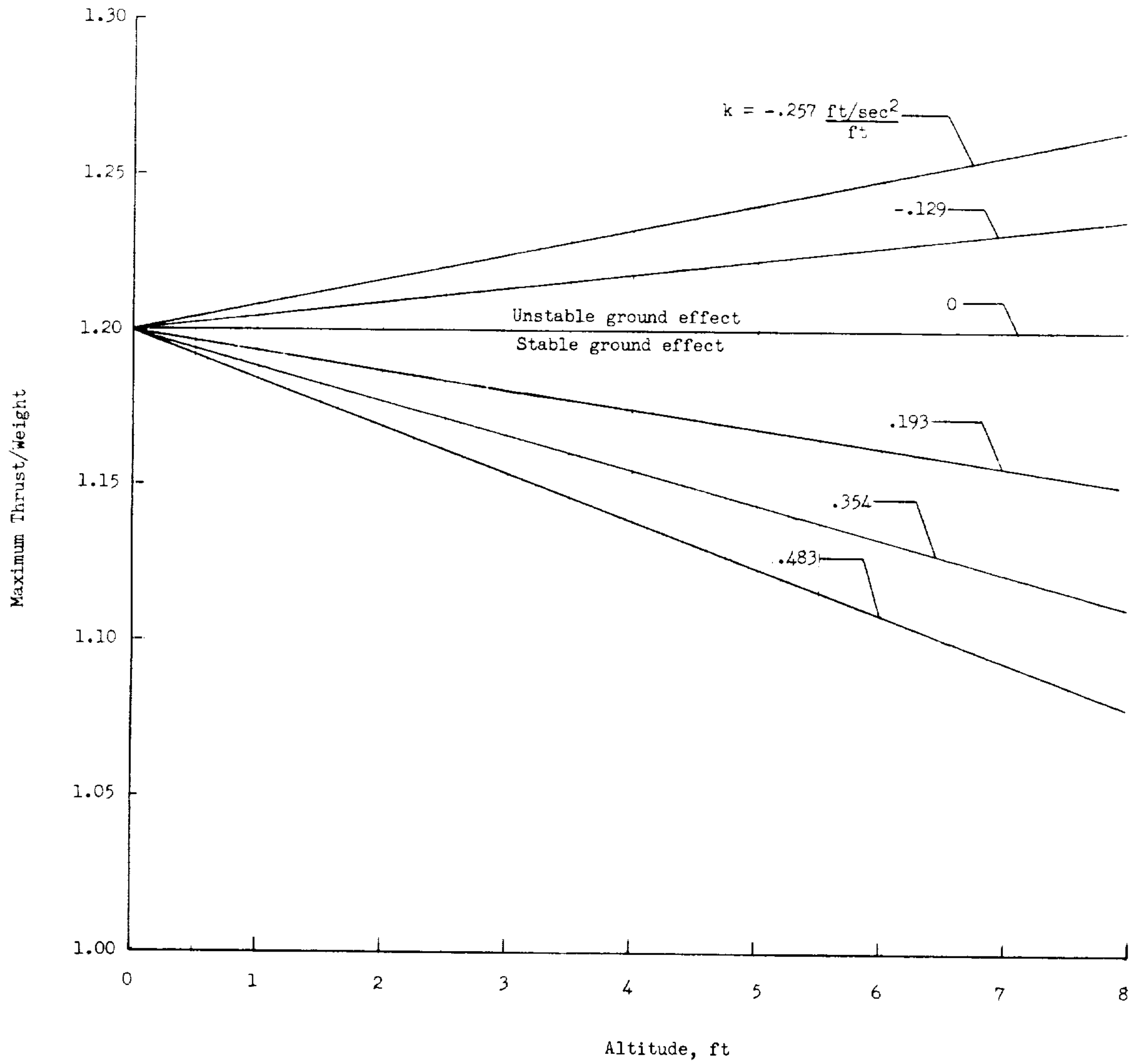

Figure 6.- Variation of maximum available thrust-weight ratio with altitude due to simulated ground effect.

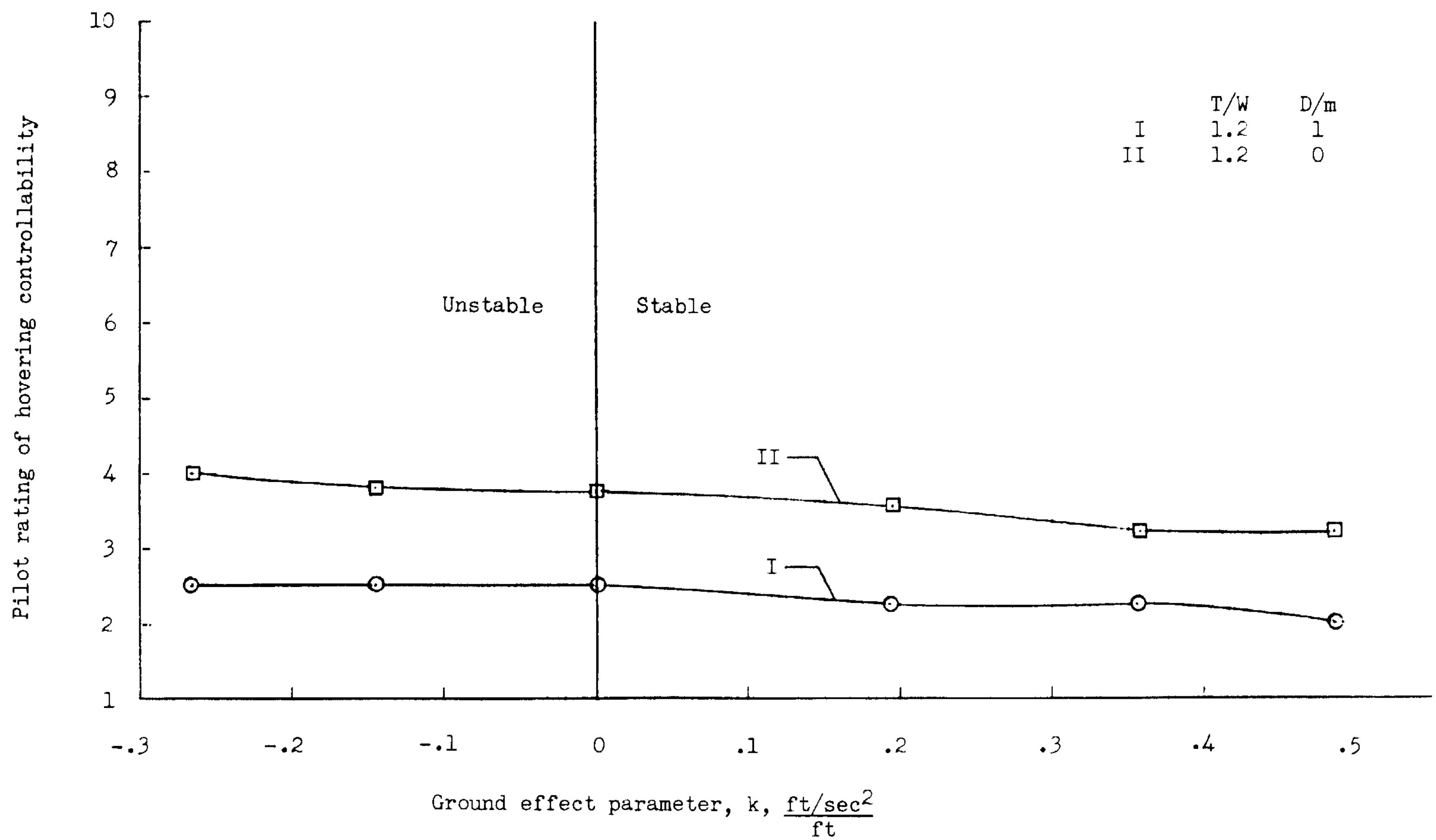

Figure 7.- Variation in pilot rating of overall controllability due to simulated ground effect with effective 0.2-second control-system time delay.